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MAN-RATED CENTRIFUGES: A NATIONAL SURVEY WITH DESIGN CONSIDERATIONS AND RECOMMENDATIONS FOR FUTURE DEVICES

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NOTICES

PREFACE

The opinions and recommendations within this report are those of the author and should not be construed to necessarily reflect Air Force policy or recommendations. Many liberties of oversimplification, generalization, and omission are inherent in a review which intends to remain brief in order that it may be read; I sincerely hope that simplification was not bought at the cost of clarity or utility to the reader.

I. INTRODUCTION

With increasing complexity of present and future aerospace systems, an increasing need has been manifest for ground simulation of mission environments. In the category of sub-orbital flight and beyond, we are building fewer vehicles, each of which costs many times more than previous vehicles, and this trend may well characterize the development of all future aerospace vehicles. In short, the ratio of Ground-Test-Time : Flight-Test-Time has increased exponentially in a manner roughly proportional to the vehicle cost and inverse to the number of vehicles built per new system. With increasing cost of a decreasing number of vehicles, an increasing amount of time is necessary and warranted for the training of personnel and for the development and test of personnel protective equipment, restraint systems, life support equipment and control design. All of these require ground-based, man-rated, environmental flight simulators. From 1959 through this date, an increasing demand for environmental simulators has been manifest in the large number of new centrifuge facilities proposed, and the modification (up-grading of performance) proposed or programmed for existing centrifuges. From published specifications of desired devices, and from the more than occasional conflict between requested performance and intended use, it seems desirable to aggregate and distribute the information identified by the title of this memorandum.

II. DEFINITIONS

Terms such as "fundamental research," "applied research," "systems test," "human tolerance," all of which perhaps were semantically inadequate in their original usage, have come to mean even more things to more people, until now it is mandatory to define specific meanings as they shall be used in this report.

A. TRAINING With regard to the motion simulators which are the subject of this report, training shall be interpreted to mean:

> The repeated exposure of selected crew members, with appropriate control and crew-compartment hardware, to the dynamic stresses of specific mission profiles, (including emergency and abort conditions). The purpose of training is to develop manual and mental skills which may measurably enhance the probability of appropriate responses to the manual and

mental performance requirements of a mission.

B. <u>SYSTEMS TEST</u> As used in this report refers to:

Test of procedures and hardware (including life support, control, restraint, escape, crew-compartment design and instrumentation display) during exposure to dynamic force environments of typical mission profiles. The purposes of system tests are to establish manned mission feasibility, performance and control limitations, and to establish the efficacy of the hardware involved.

C. <u>BASIC RESEARCH</u> As used in this report, is limited to:

The study of fundamental tropisms, reflexes, and responses, caused by exposure of organisms to simple and multiple concurrent or sequential dynamic and other stresses.

D. <u>APPLIED RESEARCH</u> here is divided into the areas of "BIOLOGICAL TOLERANCE" and "PERFORMANCE."

1. <u>APPLIED RESEARCH IN BIOLOGICAL TOLERANCE</u>

The quantitative investigation of physiologic alterations to, and mechanical-anatomic displacements of, organisms, organs and tissues, caused by the dynamic stresses of flight. This includes both simple, multiple sequential and concurrent stress interactions. Such information ultimately defines man's tolerance to flight stress and, therefore, represents the only rational basis for both vehicle design and personnel protective equipment development.

2. <u>APPLIED RESEARCH IN PERFORMANCE</u>

The quantitative investigation of performance decrements, including impairments in sensory, manual skill and judgement areas, which result from exposure to dynamic forces, both

simple and multiple, both concurrent and sequential. Such information defines man's general mission usefulness and represents the necessary basis for the design and development of instrument displays, control configurations and other factors intended to enhance performance in a man-machine system.

III. CATEGORIES OF CENTRIFUGE USE, AND CENTRIFUGE PERFORMANCE-ATTRIBUTES FOR EACH USE

In this section I shall attempt to confer specific centrifuge performance characteristics that are desirable or required for each of the categories of centrifuge usage defined under II, above.

A. TRAINING

1. Mission Profiles - To my knowledge, no flight system, programmed or planned, has normal mission profiles with boost or re-entry accelerations in excess of 20 G, at average-rates of-change-of-acceleration ("onset rates") in excess of 1 G per second. (The exception is the terminal or landing impact portion of a mission; however, the duration of landing impact acceleration is less than one second, and therefore more suitable for study on drop-towers and rocket-sleds than on centrifuges.)

2. Emergency or Abort Profiles - Data derived from the USN centrifuge at Johnsville, Pennsylvania, where the Mercury program astronauts obtained their training, shows that almost 50% of the centrifuge training time was for simulating emergency and escape conditions.

   In present and expected future systems, emergency and abort profiles may require accelerations up to 30 G and average-rate-of-change ("onset-rate") of acceleration up to 12 G per second.

3. Crew Compartment, Vehicle Controls and Restraint Hardware - The system hardware itself, or nearly identical mock-ups, are desirable for crew-training during simulated dynamic mission and emergency profiles. This need for vehicle hardware imposes a

payload requirement for training centrifuges of between two and three thousand pounds.

4. <u>Multiple Environmental Factors Desirable for Training-Centrifuges</u> - The unknown interactions of multiple concurrent stresses, the as yet undefined effects of sequential stresses and the fundamental need of training, which requires repeated exposure to the mission environments, all mitigate to demand that a centrifuge designed for training purposes should also be able to provide the vibration, buffeting, gas compositions, pressures, sound and thermal changes which could occur in a vehicle during normal flight and during emergency conditions. Of these environmental conditions, acoustic input is the easiest and cheapest to obtain, followed, in order of increasing cost and complexity, by temperature, pressure and vibration.

Vibration is a special case, and of such importance to both training needs and centrifuge design that I shall dwell on this subject.

a. With regard to training needs, a crew member's ability to cope with vibration and oscillation directly affects controllability of the vehicle by manual skills, ability to discern instrument displays, and the effectiveness of restraint and protective equipment. Vibration also gains importance by virtue of its being present at, and characteristic of, the most dynamically adverse portions of a mission, namely, the high-Q portion of boost, and re-entry, where training is most needed to assure good performance. In short, training is most needed where the environment is most adverse, and the dynamic environment is most severe where the least allowance for error exists. Vibration is therefore a highly desirable attribute of a training-centrifuge.

b. With regard to centrifuge design, vibration imposes design constraints as severe, or more severe, than the centripetal accelerations for which a centrifuge is originally required. These constraints are seen as a need for STIFFNESS (high natural frequency) of the arm structure and as additional weight at the end of the arm; both are seen as major contributions to the moment of inertia. The increased inertial moment, in turn, is manifest as higher bearing and foundation loading and as an exponential increase in power needed for a given onset rate (average-rate-of-change of acceleration). All of

these contribute to an exponential increase in the cost of the device.

(The implied trade-offs and considerations entering into design specifications of centrifuges will be dealt with in expanded form in section V.)

5. Centrifuge Artifacts and Unwanted Forces - The relatively linear or orthogonal forces and motions of flight, when generated by a ground-based centrifuge, are contaminated by forces inherent in the use of a curvi-linear device for linear problems. Major motion artifacts resulting from the use of a centrifuge are

   a. Coriolis accelerations

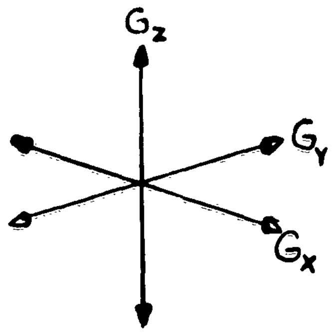
   b. Gyroscopic torques

   c. G-gradient,

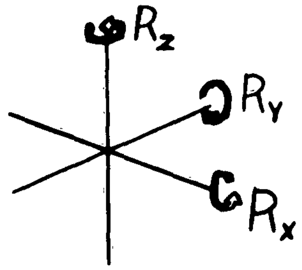
all of which relate to the selection of length (radius) of the centrifuge arm, gimbal response, and so forth, and will be dealt with in detail later in section V. Poor centrifuge design, as in an excessively limber centrifuge arm, would also create unwanted motions of "bounce" and "whip," and will also be discussed later, in section VI, B.

6. Degrees of Freedom of Motion - In addition to the rotation of the main arm of a centrifuge, six motions are possible, and often desirable. They are

   a. Three axes of translation, termed G_x, G_y and G_z



b. Rotation about these axes, R_x, R_y and R_z



Equipment which translates (vibrates) the crew members and/or their crew hardware in G_x, G_y and G_z axes we will term a "shake-table," and equipment which rotates or oscillates a crew member in the R_x, R_y or R_z axes we will term either a "motion-platform" or "gimbal," according to whether the entire gondola is rotated (gimbal) or whether the crew member is rotated with respect to the gondola ("motion-platform").

Because vibration is so necessary for adequate training, (see 4 a and b, above) I have included it in the summary below. Gimbals are also mandatory for training centrifuges in order to orient the subject with regard to a resultant acceleration vector, thus minimizing spurious vestibular inputs and artifactitious motion cues.

7. Control - The aspects of control of centrifuge motion most pertinent to training are

a. Reproducibility of a given profile (which we will assume present in most devices)

b. Open-loop Control - Command and control of centrifuge responses by means of pre-programmed tape, cams, etc.

c. Closed-loop Control - Within monitored limits, control of the centrifuge lies with the crew member pilot in a man-machine loop. The centrifuge's dynamic response to the subject's command input is translated into flight characteristic dynamics under the sponsorship of a specifically programmed computer.

On the basis of discussions with project scientists and pilots, closed loop training time is of less value

than originally anticipated. This is not to say it is of no value; however, the most experienced and respected sources I know suggest that closed-loop between the simulated vehicle controls, computer and instrument display are of major value, closed-loop control only of main arm velocity is next in value, and a completely closed-loop of controls, instruments, gimbal response and centrifuge arm velocity, all together, have not proven to have been worth their time, cost and complexity.

Closed-loop operation of controls and instrument display establishes slip-ring requirements (power and information channels), with 150-200 rings required and 400 channels desirable.

8. Summary - A centrifuge intended for use as a training device for aerospace vehicle crews should have performance attributes summarized in table I.

TABLE I

PERFORMANCE ATTRIBUTES OF AN AEROSPACE CREW TRAINING-CENTRIFUGE

Attribute	Required (Minimum)	Desirable
Radius of Centrifuge arm	30 feet	35 - 40 feet
Onset (average rate-of-change-of-acceleration)	1 G per second	10 to 12 G per second*
G_{max} (centripetal, sustained)	20 G	30 G
Payload (pounds)	1,500	3,000 or greater
Degrees-of-freedom (total 6)**	(3)	(6)
Vibration (3 axes possible)	1	3
Frequency (cycles per second)	0 - 15 cps	0 - 1,000 cps
Rotation (3 axes possible)	2	3
Temperature	$70 \pm 1^{\circ}F$	0° to $350^{\circ}F$
Acoustic energy	Characteristic of vehicle system	Characteristic of vehicle system
Control		
Open-loop	Arm, gimbals and shake table	Six-degrees of freedom
Closed-loop	Of instrument display only	Of instruments and of main arm velocity
Pressure	- 10 psig (28,000 ft.)	- 12 to 14 psig (40,000 to 70,000 ft.)
Slip rings (power and information channels)	150 - 200	400 or more

* For escape, abort and emergency training.

** Although it is necessary to characterize vibration and rotation by describing frequency response, allowable phase shift, displacement amplitudes, wave forms etc., I have omitted them here in order not to dilute more pertinent contents.

B. SYSTEMS TEST

By definition (II. B) and by inference (III. A) the systems test centrifuge is comparable to the training centrifuge in performance, with the following suggested exceptions:

G_{max} - 30 G or greater, so that the equipment may be stressed to levels greater than anticipated under both normal and emergency conditions, in order to establish safety factors.

$^{\circ}$ Freedom - 4 (2 rotation, 2 vibration)

Radius - 15 - 20 feet (minimum)

Payload - As great as possible; at least 2,000 pounds

Thermal - 0 - 350°F

Slip rings - As many as possible; at least 300 channels

C. BASIC RESEARCH

May be done on almost any centrifuge; good basic research has been done on devices ranging from four feet to fifty feet in radius.

The most important assets for basic research are

1. Personnel with good training and experience in a research specialty (cardio-vascular, metabolic etc.) and, preferably, with established experience with acceleration problems. (My own experience, with many well-trained medical officers of adequate research background who serve a two-year duty-tour at our laboratory, has convinced me that 9 to 12 months of acceleration experience are prerequisite before such investigators reach peak value in acceleration problems.)

2. Availability of Subjects, both man and animal, for use in acceleration studies. This capability is fraught with medico-legal problems, since desirable measurements may include procedures such as cardiac and arterial catheterizations, followed by acceleration exposure, and therefore dictates the next requirement, that of

3. Hospital and Analytic Laboratories of high capability. The hospital facilities are needed on ethical grounds, to handle medical emergencies which may arise from human subject experimentation. Well-staffed analytic laboratories are necessary to provide the precision of measurement which is identified with such research (e.g., blood-gas measurements).

4. Shops, Animal Facilities (vivaria) and similar support are of obvious importance and often a limiting factor.

A good example of a basic research device of quite modest performance characteristics is the Mayo Clinic centrifuge. Their basic research effort, headed by Dr. Earl Wood, has outstanding personnel, laboratories, hospital, shops, vivarium and a record of major contributions to basic acceleration research spanning two decades. However, the Mayo effort is severely impaired because of

a. The lack of human subjects (investigators have to use themselves repeatedly for procedures which include arterial and venous catheterizations) and

b. The lack of junior investigators. Dr. Wood tells me that, if provided with three additional personnel, (two investigators and a computer programmer) he could more than double his present rate of utilization of his centrifuge.

D. APPLIED RESEARCH

1. Biological Tolerance - Again, inferred by definition (II. D, 1), and similar to training centrifuge requirements, with the following exceptions:

Attribute	Required	Desirable
G_{max}	20 G	30 G or greater
Radius	20 feet	30 feet
Onset	3 G per second	10 G per second or greater
Payload	500 lbs.	1,000 lbs.

2. Performance Tolerance - Same as training centrifuge.

E. SUMMARY OF CATEGORIES OF CENTRIFUGE USAGE AND THE PERFORMANCE CHARACTERISTICS ASSOCIATED WITH EACH USE (TABLE II)

TABLE II

SUMMARY OF CATEGORIES OF USE AND ASSOCIATED SPECIFICATIONS

Category of Use	Arm Radius (feet)		Onset (G/sec)		G_{max}		Payload (lbs.)		Vibration ° Freedom		Rotation ° Freedom		Temperature (°F)		Pressure (psig)		Slip Rings		Control Loop	
	R	D	R	D	R	D	R	D	R	D	R	D	R	D	R	D	R	D	R	D
Training	30	35-40	1	>10-12	20	30	1,500	3,000	1	3	2	3	70±1°	0-350°	-10	-14	150	400	Open	Closed (arm)
Systems Test	15	>20	"	"	30	>50	2,000	>3,000	2	3	2	3	>0-350°	UNK	-10	UNK	300	UNK	Open	N/A
Basic Research	UNK	>20	UNK	3	UNK	>10	500	>1,000	0	>1	0	2	70°±1°	UNK	UNK	UNK	100	UNK	Open	N/A
Applied Research																				
Tolerance	20	30	3	>10	20	>30	500	>1,000	1	3	2	3	70±1°	0-150°	-10	-14	100	>400	Open	N/A
Performance	30	35-40	1	>10-12	20	30	1,500	3,000	1	3	2	3	70±1°	0-150°	-10	-14	150	>400	Open	Closed (arm)

NOTE: UNK = unknown, varies with system itself, or experiments desired
N/A = not applicable
R = required
D = desirable
> = "greater than"

IV. REVIEW OF NATIONAL MAN-RATED CENTRIFUGE FACILITIES

A. TABLE III, SUMMARY OF MAJOR FACILITIES BY AGENCY

Facility	Radius (feet)	Onset (G/sec)	G_{max}	Payload (pounds)	Vibration (°Freedom)	Rotation (°Freedom)	Temperature Control (°F)	Pressure (psig)	Slip Rings	Control
1. NASA										
*AMES	50	7.5	50	3,000	3	3	-75 to 257°	0.16	400	Closed Loop
AMES	30	2	6	500	****	3	None	None	425	Closed Loop
**MSC	50	3	30	3,000	0	2	-75 to 250°	0.06	450	Closed Loop
2. USN										
AMAL	50	6.5	40	1,000	0	3	0 (?)	0.16	125	Closed Loop
3. USAF										
***AMRL	20	10-12	20	500	3	3	40 - 110°	± 12	420	Open Loop
SAM	23	3	50	600	0	0 (1)*	0	0	200	Closed Loop*
4. OTHER										
USC	23	5	15	2,000	0	1	0	0	112	Open Loop
MAYO	17.7	3	14	500	0	0	0	0	45	Open Loop

NOTE:
0 = none
* = proposed and funded, but not yet in design
** = in design stage, (estimated to be available 1965-66)
*** = in construction, (estimated to be available 1964)
**** = very low frequency (less than 1 cps)

B. COMMENTS CONCERNING MAJOR CENTRIFUGE FACILITIES AND THEIR POSSIBLE USES

1. NASA

a. Ames Research Center (Moffet Field, California) - has two devices listed above. One exists, the other is proposed and funded, but not yet designed; it is not expected to be completed until 1967. Uses: Training, systems tests, basic research, applied (tolerance and performance). The device currently in operation is being used for flight-control studies primarily.

b. Manned Spacecraft Center (Houston, Texas) - This centrifuge is in the preliminary design phase, and is not expected to be operational until 1966. Uses: Systems test, (limited usefulness for training and applied), basic research.

2. USN

a. Aviation Medical Acceleration Laboratory (Johnsville, Pennsylvania) - This device is presently in operation, but it has a modification (up-grading) program in the construction phase, and modification is expected late 1963. This is the largest U.S. man-rated centrifuge. Uses: Systems test, (limited usefulness for training and applied), basic research.

3. USAF

a. Aerospace Medical Research Laboratories (Wright-Patterson AFB, Ohio) - This device is under construction and is expected to be in limited operation December 1963. Full operation is expected by mid-1964. This is the only U.S. Manned centrifuge with vibration capabilities (actually, up to six-degrees-of-freedom of motion) expected to be operable before 1967. Uses: Systems test, applied (tolerance and performance), basic research.

b. School of Aerospace Medicine (Brooks AFB, Texas) - Closed-loop operation of main-arm velocity control, and one-degree of freedom (rotation) are programmed modifications expected to be available by 1964-1965. Uses: Training (limited usefulness), "clinical evaluation," and basic research.

4. OTHER

a. University of Southern California (Los Angeles, California) - Scheduled for modifications this year which significantly change the previous performance characteristics. It is often used by nearby airframe manufacturers and other agencies. Uses: Basic research and limited systems research.

b. Mayo Clinic (Rochester, Minnesota) - This device has been used for basic research only. It was refurbished five years ago, under USAF sponsorship, following a decade of inactivity.

Both USC and Mayo centrifuges are brought into motion by clutches coupling the centrifuge arms to massive flywheels which previously were slowly brought up to appropriate rates of rotation. Their propulsion system is therefore less versatile with regard to following complex acceleration time-history profiles.

C. THE NATIONAL MIS-MATCH EXISTING BETWEEN CENTRIFUGE NEEDS AND CENTRIFUGE RESOURCES - Comparison between table II (Categories of Use) and table III (Summary of Major Facilities) shows the following:

1. TRAINING - The required performance capabilities in this category are not met by any centrifuge, existent or proposed. The nearest contender is still quite distant, being the new device proposed for AMES and not yet in the preliminary design phase. It is possible that the ambititious performance specified will not be possible with the 50 foot radius also specified.

2. SYSTEMS TEST - Same as "Training" above.

3. BASIC RESEARCH - These requirements are closely approached, met or exceeded by every device in table II.

4. APPLIED RESEARCH

a. Tolerance - If we require vibration, heat and altitude, no facility exists which is adequate, although AMES (proposed) and AMRL (in construction) can do this job when they become operational.

b. Performance - The same as true of tolerance, but in addition to AMES and AMRL, the AMAL device may also meet this need if gimbal oscillation can produce inputs close to vibration inputs.

It appears that, of the eight major U.S. manned centrifuges, (five now operational, one proposed, one in design and one under construction), only one, AMES (proposed) may be suitable for aerospace vehicle training and systems test; all eight are suitable for basic research; two (AMES and AMRL) will be suitable for applied research in tolerance; and three (AMES, AMRL and AMAL) are suitable for performance studies.

V. CENTRIFUGE DESIGN, SPECIFICATIONS AND TRADE-OFFS

Perhaps the best way to appreciate the mechanical and economic constraints, as well as the trade-offs that they create, is to consider the design requirements of a hypothetical device. We will assume that this device is for near future, orbital flight, and that its use will be:

50% for training purposes

25% for system test

25% for applied research

The most recent references pertinent to such a facility are:

Reference (1) "Report Engineering Study and Design Criteria of a Flight Acceleration Facility" NASA, MSC, November 30, 1962 (Volume I-IV), by Ford, Bacon and Davis, Inc. (Engineers), assisted in this study by McKiernan and Terry Corporation (they designed and built the AMAL at Johnsville, Pennsylvania), Cornell Aeronautical Laboratory, Inc., The Franklin Institute, and Raytheon Company. (Franklin Institute and Raytheon are the prime contractor and control-system subcontractor, respectively, of the AMRL centrifuge now under construction).

Reference (2) "Design Study for an Acceleration Research Device" by K. C. Drome of the Rucker Company, ASD Technical Report 61-425, August 1961.

Reference (3) "Feasibility and Design Study for an Advanced Human Environmental Research Accelerator" by the McKiernan and Terry Corporation, WADD Technical Report 60-225, March 1960.

Reference (4) "Feasibility Study for an Advanced Device for Studying the Effects of Acceleration on Man" by G. W. Ehrsam, Jr., American Machine and Foundry Company, WADD Technical Report 60-187, March 1960.

I should like to consider, in order of diminishing need for depth of consideration

A. Arm Radius, and its effect on:

1. The torque required

2. The artifacts of G-gradient and coriolis accelerations

B. Onset (or average rate of change of acceleration)

C. Vibration as well as the reason for

D. Interchangeable Gondolas and, very briefly, note the lack of experienced and well-trained

E. Personnel so that the reader may be reminded that a tool is no better than the people available to utilize it.

A. ARM RADIUS - With only one exception every machine now proposed or in design has specified a radius from 40 to 60 feet, with 50 feet being typical (as well as a numerical average). What do these radii mean in terms of cost and in terms of incompatibility to other desirable centrifuge characteristics? On what basis should we specify the radius of a centrifuge?

The radius, for any given payload accelerated to maximum acceleration (G_{max}) in a given time, defines cost, by

1. The Torque Required, which is proportional to the cube of the radius, or to $(L)^3$. Since the strength of the arm, counterweight mass, foundation and propulsion source are all also proportional to the torque required, it may be said, that in round numbers,

"THE COST OF A CENTRIFUGE WITH FIXED STIFFNESS, PAYLOAD ONSET-RATE AND MAXIMUM ACCELERATION, IS ALMOST PROPORTIONAL TO THE CUBE OF THE RADIUS OF THE CENTRIFUGE."

This is an approximation, quite obviously, and is in part based on the following: (from Cappel, vol. IV, section 27, ref. 1) which is concerned with (a) gimbals and payload and (b) cross section of the arm.

a. For a given gimbal mass, the moment of inertia is proportional to the square of the length, while for a given centripetal acceleration the angular velocity is inversely proportional to the square root of the radius. The acceleration required to reach this angular velocity in a given time is directly proportional to the peak angular velocity, and thus inversely proportional to the square root of the radius. Therefore the torque required to accelerate the given gimbal inertia in the given time to the maximum angular velocity is proportional to the 3/2 power of the radius, or $(L)^{3/2}$.

b. For an arm of constant cross section, the torque required to accelerate the arm itself is proportional to the square of the length, and directly to the weight, which in turn is directly proportional to the length, so that the torque required to accelerate a constant cross section arm is proportional to the cube of the length, or $(L)^3$.

c. However, the dimensions of the arm will probably be determined mainly by its stiffness. Since stiffness means exponentially increasing inertia (see figure 4), then increasing the radius, while keeping STIFFNESS, gimbal-payload, onset and peak acceleration constant, puts cost approximately proportional to the cube of the radius.

Or to state it another way, doubling the length of the centrifuge arm may increase the cost by a factor of eight times (e.g., to increase a thirty foot arm to a sixty foot arm may increase the cost from, say 4 million dollars, to 32 million dollars). We are required therefore, to think carefully about why an arm should be a specific length (radius).

2. The radius defines the magnitude of the two major artifacts inherent in the use of centrifuges, which are the G-GRADIENT, and CORIOLIS ACCELERATIONS (forces).

In figure 1 is plotted the per cent of any given acceleration existing as a G-GRADIENT, for different subject positions, all as a function of the length (radius) of a centrifuge arm.

In figure 2 is plotted the per cent of a given (10 G) centripetal acceleration, existing as a CORIOLIS ACCELERATION, for a 10 foot per second motion directed toward the axis of rotation. The coriolis acceleration is plotted as a function of arm length (radius). This motion may occur, as an example, in a simulated re-entry profile, when the astronaut would attempt to control the vehicle by imparting a forward (or other) corrective motion to a control stick or pedal. A force (Coriolis) would be generated at right angle to his corrective motion, and this lateral force (albeit spurious and unwanted) would deflect the control stick laterally with a magnitude relating to the radius of the centrifuge, as shown in figure 2.

This point is verified in volume 1, section 2, and volume 4, section 27, of reference (1), by the Cornell Aeronautical Laboratory and the Franklin Institute, respectively.

B. <u>ONSET</u> - Volume 1, section 2 of reference (1) establishes orbital vehicle emergency and abort requirements of up to 10 G per second.

Figure 3 plots the moment of inertia (as pound-feet per second^2) of an assumed 10,000 lb. gimbal-payload mass (a 7,000 lb. gimbal assembly will probably be necessary for a test-payload of 3,000 lbs.) and inertial moments of centrifuge arms with different lengths and different stiffnesses (natural frequency, given in cps. or cycles-per-second). The points labelled "TYPICAL" give the approximate inertial moments contributed by the gimbal-payload and the typical 5 cps, 50 foot arm, currently proposed for centrifuges, which totals to 8.75 X 10^5 lb. ft. sec^2. The points labelled "Alternative recommended", a 35 foot, 15 cps (natural frequency) total 5.45 X 10^5 lb. ft. sec.^{2}, and represent a 30 per cent reduction in the mass moment of inertia. This means that, given a constant torque (available power), a 30 per cent decrease in inertial moment would increase the onset-rate by at least 30%, and possibly higher, since we have neglected the inertial moment of the counterweight, windage drag and similar contributors (all of which would also be reduced proportionately) in order to simplify the gross concept.

In figure 4 angular velocity (radians per second) is plotted as a function of increasing centrifuge radius necessary for centripetal acceleration of 10 G.

Because Coriolis acceleration is proportional to angular velocity, figure 4 is similar to figure 2, but is shown here anyway since long centrifuge arms have been justified partly on the basis of reducing vestibular input to the subject. Of course increasing the radius reduces the angular velocity necessary to produce a given centripetal acceleration (see figure 4); but centripetal acceleration is proportional not only to the radius, but also to the <u>square</u> of the angular velocity, and doubling the radius therefore reduces the angular velocity by asymptotically diminishing amounts. At 10 G centripetal, an angular velocity of 2.3 radians per second (viz., 132 degrees per second) is still present <u>even with a 60 foot radius</u> centrifuge arm. Figure 4 does not justify centrifuge arms in excess of 35 feet on this basis.

More important the semi-circular canals are transducers of <u>angular acceleration</u>, and are therefore responsive to <u>changes</u> in angular velocity The onset rate, or the rate-of-change of angular velocity appears to be a potentially important source of artifactitious vestibular input. However, it was shown previously that angular acceleration is directly proportional to peak angular velocity, and this has been seen, in figure 4, to be a relationship characterized by ever-diminishing gains with a cut-off point somewhere around 30 to 35 feet (radius). The angular accelerations at the gimbals become quite high, particularly during subject-realignment at the onset and offset of an experiment, and vestibular input therefore is expected to relate more to gimbal acceleration rates than to main centrifuge arm accelerations.

Finally, as suggested by K. L. Cappel (vol. 4, section 27 of reference (1), the concept that the longest possible arm will cause the least amount of spurious-force input to a centrifuged subject needs to be revised:

"For a given arm angular velocity, the gyroscopic torque is proportional to the angular velocity, and thus to $1/\sqrt{L}$, but since the <u>bending deflection</u> increases as L^3, (for a constant cross-section arm), the lower gyroscopic torques of the longer arm may yet produce higher unwanted forces, whose magnitude can not be exactly predicted since they depend on the unknown amplitude. However, since these (amplitude) accelerations are proportional to the square of the frequency, they increase rapidly as resonance conditions

are approached." These are the spurious "bounce" and "whip" inputs mentioned in section III, A., 5.

To sum up, the low natural frequency, long radius-cantilever arm not only is expensive and mechanically incompatible with the real need for also simulating vibration concurrent with prolonged acceleration, the long arm of low natural frequency also produces uncontrollable and unpredictable spurious inputs whose magnitude equals or exceeds those forces whose reduction was attempted by increasing the length of the arm.

C. VIBRATION - At the risk of being repetitious, the need for vibration will again be emphasized. The present proposed designs could not tolerate vibration in the biologically vital frequency range, from 1 to 10 cps, since they have a 5 cps resonance and would deflect excessively and possibly catastrophically if excited by 1 to 10 cps vibration at the gondola. The alternative arm, shown in figure 3, would permit vibration at 1 - 10 cps to be at least an option for the gondola since the alternative arm is stiffer, with a natural frequency of 15 cps.

D. INTERCHANGEABLE GONDOLAS - At centrifuge facilities where more than one category of use has existed, experience has shown that severe reduction of rate-of-utilization exists unless provision is made for relatively rapid interchange of gondolas. For example, at the USN facility, Johnsville, Pennsylvania, about one-half of each working-year of centrifuge time has been spent (effectively "lost") in alterations of the gondola and in check-out procedures. Most of this could have been accomplished on the ground in a second gondola, thus effectively doubling the rate of utilization of a facility whose replacement cost has been estimated at 35 million dollars, (see "Interim Report of the Scientific Advisory Board, Ad Hoc Committee on Life Sciences/Human Factor Facilities on Human Centrifuges--National Resources and Needs, 30 October 1961). Interchangeability of gondolas and/or gondola equipment has been included in the forthcoming AMRL and Johnsville modifications. It is also planned for the MSC device, and is a desirable attribute for all future centrifuges.

E. PERSONNEL - Few, if any, of the 40 or more major dynamic motion simulators (see NAS-NRC Report No. 903, by H. E. von Gierke and E. Steinmetz, 1961) are adequately staffed at this time; by "adequate" I mean quality as well as quantity of staff. There is, in fact, a major motion simulator facility of the one-half million dollar category of cost, which has no trained investigatory personnel and no available panel of human test subjects.

VI. DISCUSSION

This presentation, it must be emphasized, is limited in its view into the future, and has considered centrifuges of the cantilever-type only.

It is entirely possible that need for one, two or even three hundred foot radius centrifuges may someday exist and be justifiable on a basis not yet known, or unique to a particular aerospace vehicle system.

Centrifuges of other than cantilever designs should also be considered as possibilities for the future. For example, a very large diameter, massive flywheel-circular track combination has been proposed by Holloman AFB. This interesting facility is conceived of as being capable of entire mission simulation (except for weightlessness), and will be designed to handle an entire vehicle and its crew, subjecting them to dynamic, thermal and barometric environments of a mission. In addition, it is proposed to have an adjacent facility which provides the barometric and radiative environment of outer space so that the crew can establish "extra-terrestrial" exploration procedures. The whole complex is intended to reproduce the environment and duration of any aerospace mission, with the maximal fidelity possible even in the face of our earthbound inability to simulate weightlessness. Time and requirements will decide whether this concept is necessary and/or feasible, both mechanically and in terms of cost versus usefulness.

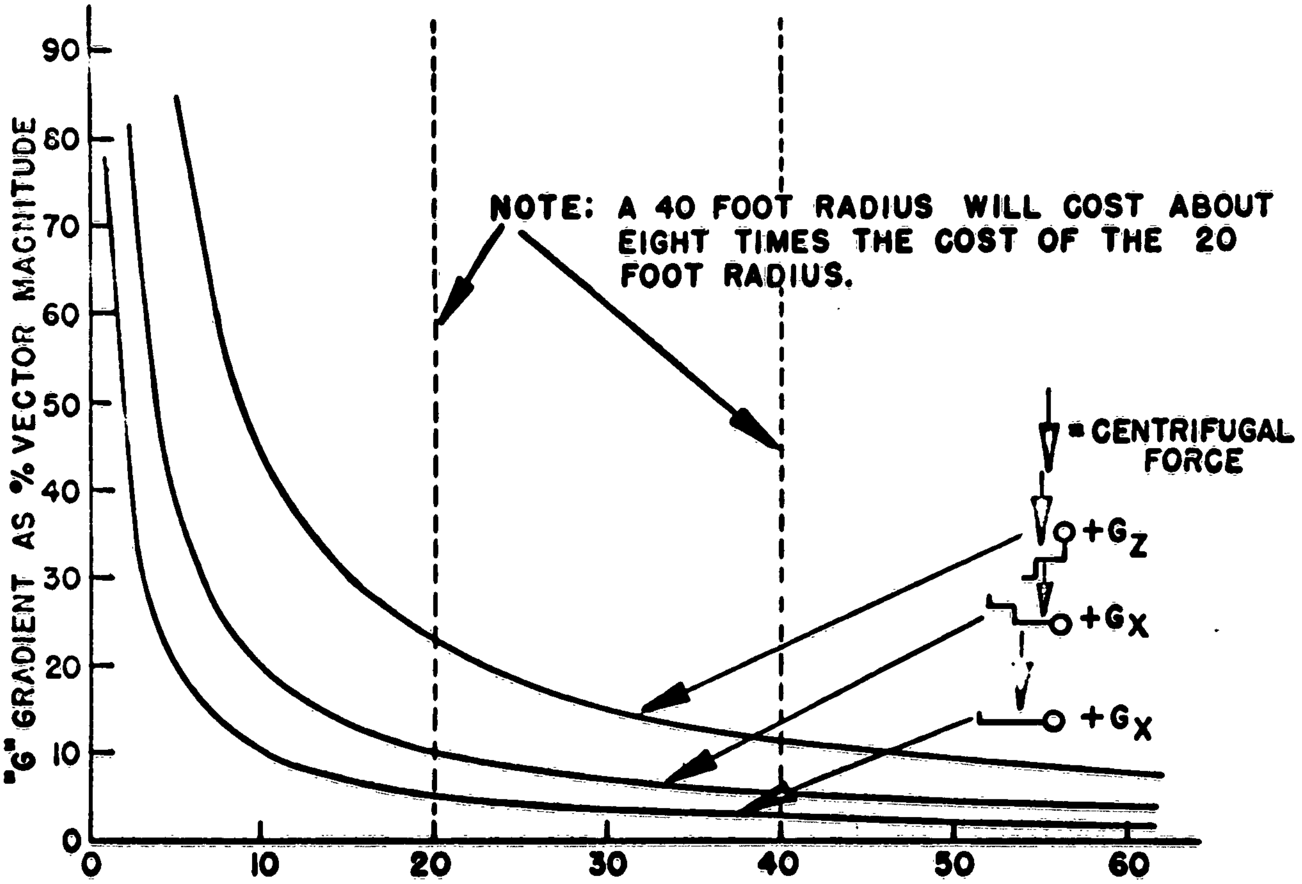
VII. SUMMARY

A. It has been the thesis of this memorandum-report that the need for man-rated centrifuges will continue to increase, that more devices of this type will be proposed and built within the next decade, and that performance (and cost) of these devices will also continue to increase.

B. Categories of use of man-rated centrifuges have been presented and compared to our national capabilities; our capabilities were found to be less than our needs.

C. In order to transmit experience gained by the author in establishing specifications for man-rated centrifuges, information was offered relating to major trade-offs that influence final design configuration, cost and usefulness of these devices.

FIGURE I



"G" GRADIENT AS % VECTOR MAGNITUDE
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
NOTE: A 40 FOOT RADIUS WILL COST ABOUT EIGHT TIMES THE COST OF THE 20 FOOT RADIUS.
= CENTRIFUGAL FORCE
+G Z
+G X
+G X

FIGURE 2

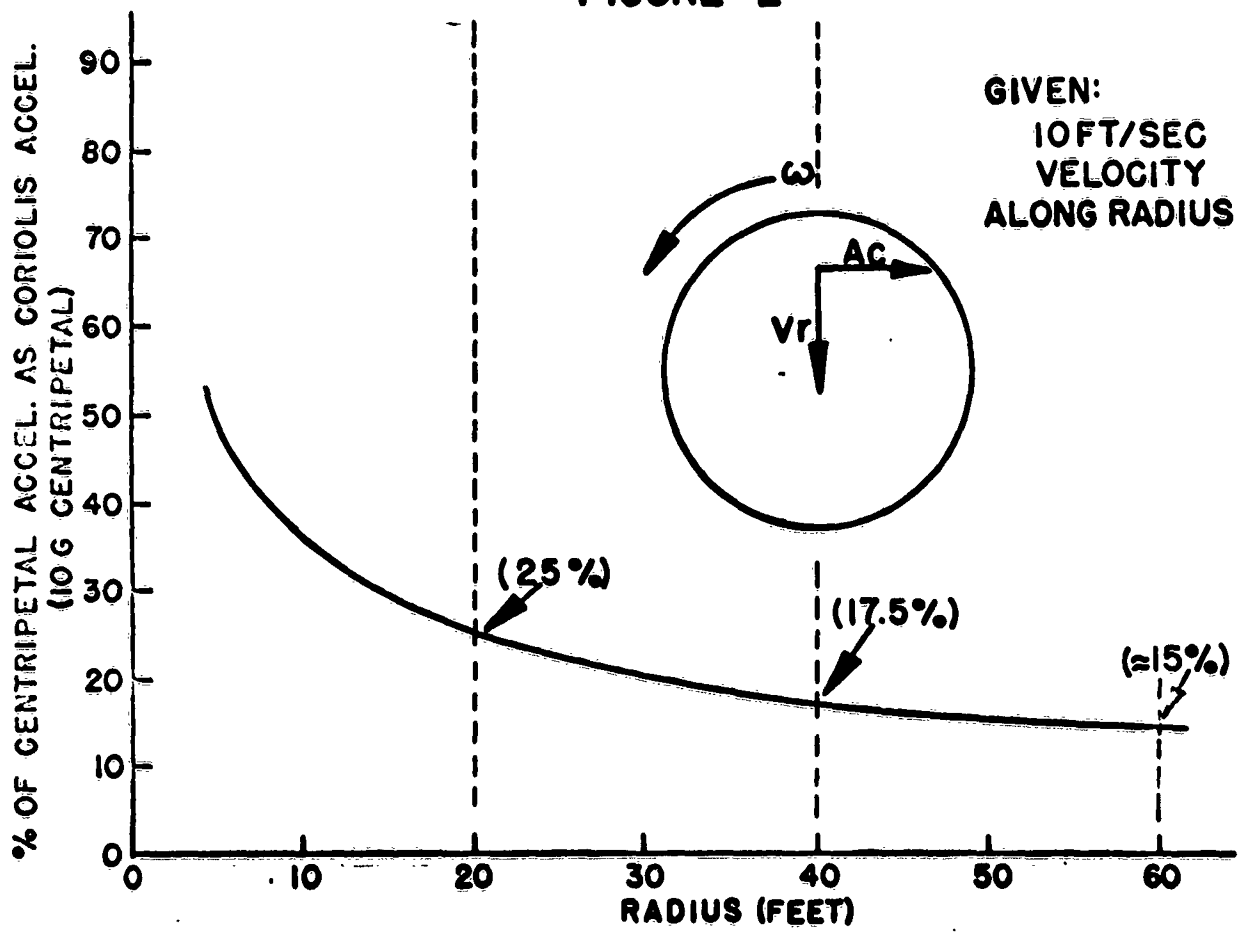
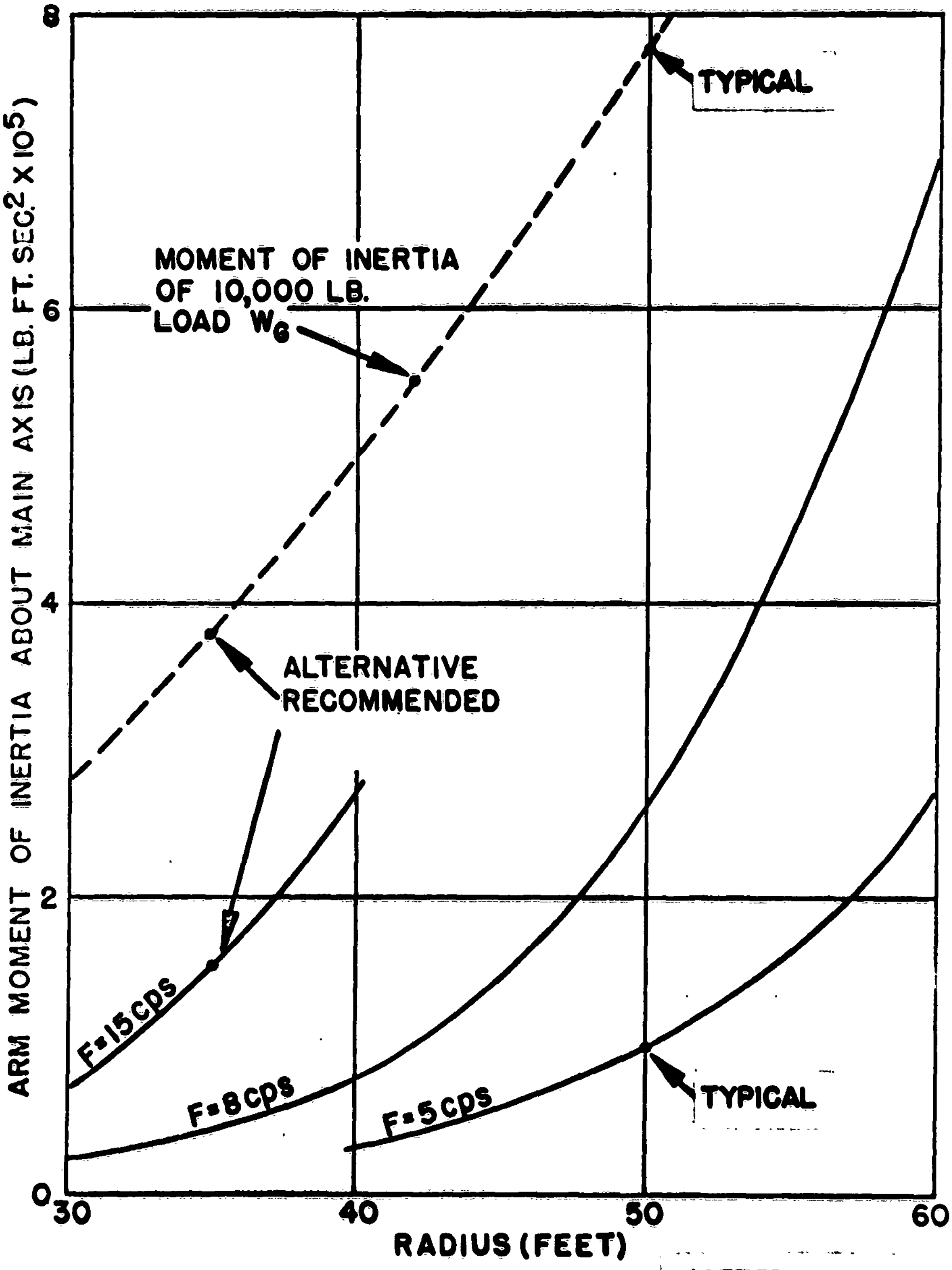
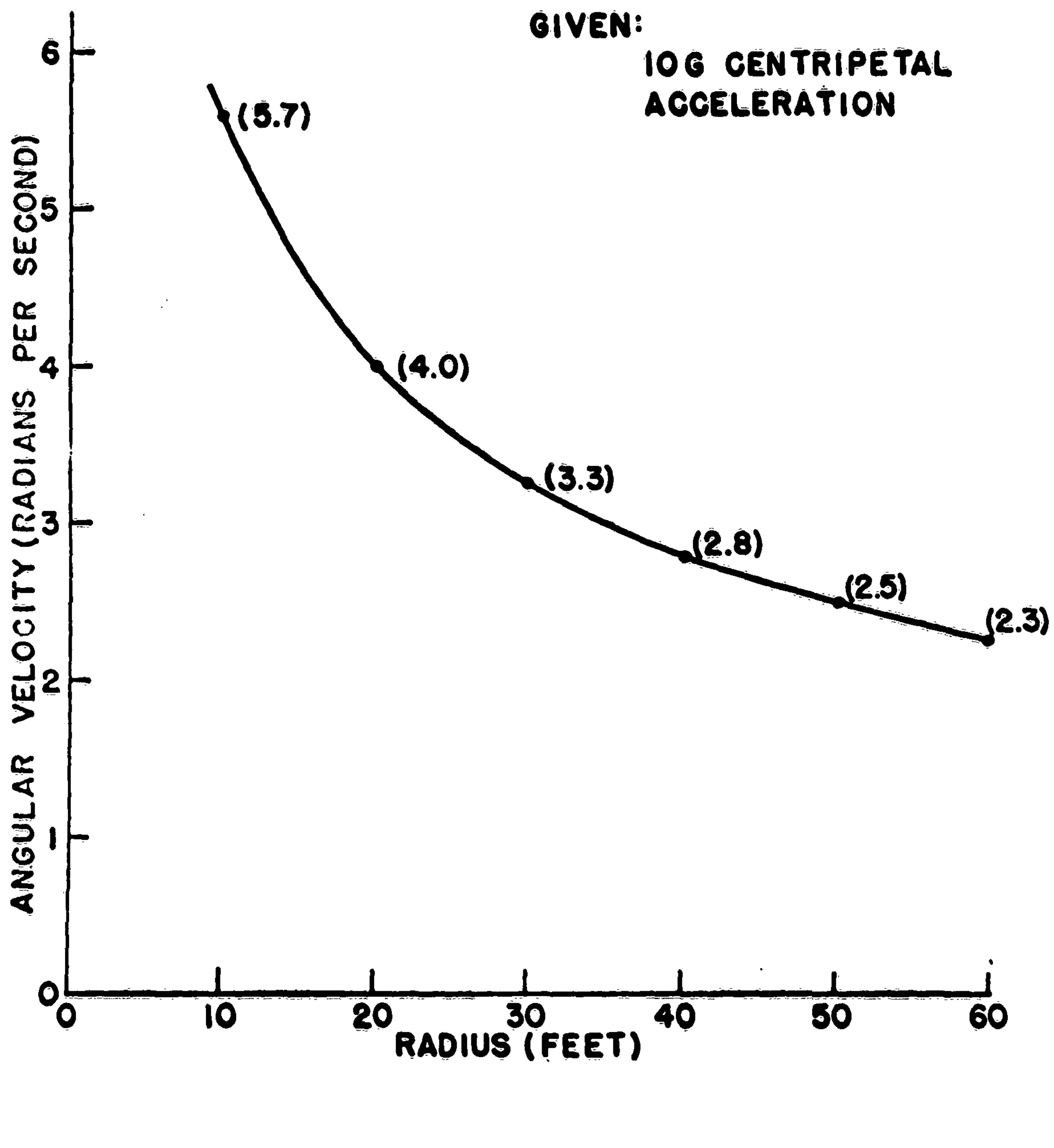

% OF CENTRIPETAL ACCEL. AS CORIOLIS ACCEL.
(10 G CENTRIPETAL)
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
RADIUS (FEET)
GIVEN:
10 FT/SEC
VELOCITY
ALONG RADIUS
ω
Ac
Vr
(25%)
(17.5%)
(≈15%)

FIGURE 3



(AFTER K. CAPPEL)

FIGURE 4


GIVEN:
10G CENTRIPETAL ACCELERATION
ANGULAR VELOCITY (RADIANS PER SECOND)
0
1
2
3
4
5
6
(5.7)
(4.0)
(3.3)
(2.8)
(2.5)
(2.3)
0
10
20
30
40
50
60
RADIUS (FEET)